AD NUMBER

AD867291

NEW LIMITATION CHANGE

TO

Approved for public release, distribution unlimited

FROM

Distribution authorized to U.S. Gov't. agencies and their contractors; Critical Technology; MAR 1970. Other requests shall be referred to Naval Air Systems Command, Washington, DC 20360.

AUTHORITY

USNASC ltr, 26 Oct 1971

R-8173

OPTIMIZING THE COMBINATION OF STRENGTH AND STRESS-CORROSION RESISTANCE OF 7075 ALUMINUM BY THERMAL-MECHANICAL TREATMENTS

Final Report

(1 April 1969 through 31 March 1970)

March 1970

By

A. J. Jacobs

Prepared Under Contract No. N00019-69-C-0339

for

Naval Air Systems Command
Department of the Navy

By
Rocketdyne
A Division of North American Rockwell Corporation
Canoga Park, California

This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with the approval of the Naval Air Systems Command.

Air 5203/A Wash, D.C. 20360

62

R-8173

OPTIMIZING THE COMBINATION OF STRENGTH AND STRESS-CORROSION RESISTANCE OF 7075 ALUMINUM BY THERMAL-MECHANICAL TREATMENTS

Final Report

(1 April 1969 through 31 March 1970)

March 1970

By

A. J. Jacobs

Prepared Under Contract No. N00019-69-C-0339

for

Naval Air Systems Command
Department of the Navy

By
Rocketdyne
A Division of North American Rockwell Corporation
Canoga Park, California

AIR-52031A
Wash. D.C. 20360

FOREWORD

This report was prepared by the Metals Group of the Research Organization of Rocketdyne, a Division of North American Rockwell Corporation, in compliance with Contract No. N00019-69-C-0339, Naval Air Systems Command, U.S. Navy, covering the period from 1 April 1969 through 31 March 1970. The contract monitor was Mr. R. Schmidt.

The principal investigator was Dr. A. J. Jacobs with Dr. R. P. Frohmberg providing technical supervision. Helpful discussions held with Dr. W. T. Chandler and the experimental assistance provided by Messrs. G. E. Dyer and H. G. Hayes are gratefully acknowledged.

ABSTRACT

Yield strengths exceeding 70,000 psi, coupled with stress-corrosion times-to-failure in excess of 30 days (at applied stresses of 75% of yield), were obtained by a two-step overaging/press forging operation. These properties were achieved in the center of blocks that were 3 to 4 inches thick before reductions of 10 to 20%. Longitudinal reductions were found to produce improvements in short transverse yield strength varying from 10,500 to 13,400 psi. Such results typified the strong dependence of mechanical properties on working direction noted in this study. Exploratory heat treatments incorporating several departures from standard practice gave encouraging results in another phase of the program.

CONTENTS

ILLUSTRATIONS

TABLES

TABLE (Continued)

INTRODUCTION

The objective of earlier Rocketdyne programs with the Naval Air Systems Command was to determine the mechanism of stress-corrosion cracking in 7075 and related aluminum alloys (Ref. 1 and 2). The objective of the present and immediately preceding programs (Ref. 3) is to apply the knowledge and improved understanding of the stress-corrosion mechanism so gained to the optimization of properties of these alloys. Optimization in the case of 7075 is meant to include the yield strength of the -T6 temper (at least 70,000 psi) and the stress-corrosion resistance of the-T73 temper (at least a 30-day lifetime in an alternate immersion test under an applied stress of 45,000 psi). The methods for achieving an optimum combination of properties involve thermal-mechanical treatments employing conventional mill equipment.

It is well known that the age hardening of aluminum alloys is associated with a decrease in stress-corrosion resistance. The mechanistic phase of the earlier programs (Ref. 1 and 2) showed that this decrease is most pronounced when the aging is accelerated by a prior mechanical treatment. Furthermore, it has been shown that age hardening is more detrimental to stress-corrosion resistance than is strain hardening. It has become clear that a certain amount of strain hardening is required if an optimum combination of strength and stress-corrosion resistance is to be achieved.

Strain hardening is most beneficial when carried out subsequent to all aging operations and on well overaged material. Performed in this manner, the strain hardening does not induce additional aging, such as it does in an underaged condition (relative to -T6), in -T6 itself, or in a slightly overaged condition (relative to -T6).

The mechanistic studies (Ref. 2) disclosed an important correlation between ($MgZn_2$) particle size (d), yield strength (σ_y), and stress-corrosion time-to-failure (t_f). If 7075-T6 is overaged for increasing times, t, up to t=10 hours at 350 F, d and t_f increase rapidly while σ_y decreases rapidly. From t=10 to t=210 hours, the rates of increase in d and t_f and of decrease in σ_y are much more gradual. Thus a critical particle size ($\sim 85\text{Å}$) is associated with the -T73 condition (10 hours at 350 F), and further aging of the -T73 effects little additional improvement in the stress-corrosion resistance.

The present program consists of two parts. The first is an exploratory heat treatment of 7075 alloy that incorporates several departures from standard practice: a natural aging period prior to artificial aging above the G.P. zone solvus temperature; slow heating to the artificial aging temperature; and interruption of artificial aging. Nicholson and co-workers (Ref. 4 and 5) have shown that each of these procedures can affect the concentration and distribution of vacant lattice sites, which in turn

control the homogeneous nucleation of precipitates within the grains and the width of the precipitate-free zone (PFZ) adjacent to the grain boundaries. Precipitate and PFZ characteristics are tied in with the stress-corrosion mechanism. In a program conducted for NASA (Ref. 6), a direct connection was demonstrated between the supersaturated vacancy concentration and stress-corrosion susceptibility. Quenched-and-aged specimens of 7075 alloy, which contained the lowest concentration of quenched-in vacancies, performed significantly better in stress-corrosion tests than specimens of higher vacancy concentration. The aging treatments in the exploratory heat treatment were terminated after the $MgZn_2$ particle size had reached a critical value ($\sim$85Å), as measured by x-ray line broadening techniques.

In the second part of the present program, various heat treated conditions including 7075-T6 and -T73 were press forged to increase strength, and post-forging heat treatments were conducted in some cases to improve stress-corrosion resistance. The material for press forging was derived from rolled plate or hand forgings. The effectiveness of the foregoing thermal-mechanical treatments was determined from tensile and alternate immersion tests.

EXPERIMENTAL PROCEDURE

MATERIAL

The starting material consisted of two 7075-T651 rolled plates and three 7075-T73 hand forgings. The rolled plates measured 24 by 12 by 2 3/4 inches and the forgings 4 by 6 by 8 inches. The forgings conformed to MIL A-22771-B. Plate and forging compositions are shown in Table I, and representative tensile properties reported by the suppliers appear in Table II. The electrical conductivity reported for the forgings was 38.5-40.0.

EXPLORATORY HEAT TREATMENT

An exploratory heat treatment was conducted as follows: Specimens of 7075-T651 were solution treated, water quenched, and naturally aged for 23 hours before being heated slowly ($\sim$90 F/hr.) to an artificial aging temperature of 350 F. This temperature exceeds the G.P. zone solvus for 7075 alloy. One group of specimens was aged without interruption at 350 F. The aging of two other groups was interrupted for 41 and 209 hours, respectively; during these periods the specimens were again allowed to age naturally. The final step in the treatment was a stabilization age at 250 F, which was necessitated by the metastability of the reverted (artificially aged) structure.

TABLE I

COMPOSITION OF 7075 STARTING MATERIAL (Reported by Suppliers)*

Temper	Form	Heat No.	Weight Percent									
			Zn	Mg	Cu	Fe	Cr	Si	Mn	Ti	Other	Al
7075-T651	Rolled Plate	98158	5.10-6.10	2.10-2.90	1.20-2.00	.70 max.	.18-.40	.50 max.	.30 max.	.20 max.	.15	Bal.
7075-T73	Hand Forging	W-12483	5.46	2.48	1.63	.23	.19	.07	.01	.02		

* Rolled plate supplied by Ducommun Metals and Supply Co., Vernon, California

Hand forgings supplied by Weber Metals and Supply Co., Paramount, California

TABLE II

TENSILE PROPERTIES OF 7075 STARTING MATERIAL (Reported by Suppliers)*

Temper	Form	Heat No.	Direction	Yield Strength (psi)	Tensile Strength (psi)	Elongation
7075-T651	Rolled Plate	98158	Short Transverse	60,000 min.	70,000 min.	3% in 2 inches
7075-T73	Hand Forgings	W-12483	Longitudinal	56,800	68,150	13.0% in 1.4 inches
			Long Transverse	56,200	68,000	6.4% in 1.4 inches
			Short Transverse	53,350	69,850	5.7% in 1.4 inches

*Rolled plate supplied by Ducommun Metals and Supply Co., Vernon, California

Hand forgings supplied by Weber Metals and Supply Co., Paramount, California

Structural changes were monitored by means of hardness measurements and x-ray line broadening techniques. Comparison of η-phase ($MgZn_2$) intensities and line breadths with the values obtained from a 7075-T73 standard indicated the relative volume fractions and particle sizes in the samples, respectively. A correlation had been found earlier (Ref. 2) between η-particle size and stress-corrosion time-to-failure (t_f) of notched, overaged 7075 specimens. The tensile and stress-corrosion properties of the heat treated material were measured using smooth specimens of short transverse orientation.

PRESS FORGING

In this part of the program, four press forging operations were carried out at a local shop (Carlton Forge Works) using a United 1500-ton steam hydraulic press. Certain parameters were varied during the four operations. These variables were: material origin, heat treatment, preheat, postheat, forging temperature, forging direction, percent reduction, and material thickness. The conditions under which each forging operation was performed are summarized in Tables III through VI.

Operation No. 1: Overaged Tempers - Use of Preheat

The first press forging operation was carried out on eight overaged 7075 aluminum blocks originating from as-received 7075-T651 rolled plate (Table III). These blocks measured (machined) approximately 3 1/8 in. x 2 7/8 in. x 2 5/8 in. and were forged in the short transverse direction (2 5/8 in. dimension). The processing sequence was as follows. After being cut

TABLE III

EXPERIMENTAL PARAMETERS - FIRST PRESS FORGING OPERATION

Material Origin	Block Numbers	Heat Treatment	Block Dimensions (in.)			Forging Direction	Percent Reduction	Other Conditions
			L.	L.T.	S.T.			
7075-T651 Rolled Plate	A1	SHT at 895 F for 2 hrs., WQ,-T6 age, 10 hrs. at 350 F	3.2	2.8	2.7	S.T.	10	P.-eheated at 325-350 F for 1½ hrs.
	A2	"	"	"	"	"	15	"
	A3	"	"	"	"	"	20	"
	A4	"	"	"	"	"	22½	"
	A5	Same as above, except 15 hrs. at 350 F after -T6 age	"	"	"	"	10	"
	A6	"	"	"	"	"	15	"
	A7	"	"	"	"	"	20	"
	A8	"	"	"	"	"	22½	"

TABLE IV

EXPERIMENTAL PARAMETERS - SECOND PRESS FORGING OPERATION

Material Origin	Block Numbers	Heat Treatment	Block Dimensions (in.)			Forging Direction	Percent Reduction	Other Conditions
			L.	L.T.	S.T.			
7075-T651	B1	SHT at 895 F for 2 hrs., WQ, -T6 age, 10 hrs. at 350 F.	3.1	2.8	2.6	Unforged Control	---	No preheat in any of forging operations below.
	B2	"	"	"	"	S.T.	10.0	Water quenched after pressing.
	B3	"	"	"	"	"	10.6	Attempted to press in two equal steps with quenching after each step.
	B4	"	"	"	"	"	15.5	Attempted to press in three equal steps with quenching after each step.
	B5	"	"	"	"	"	21.8	Attempted to press in four equal steps with quenching after each step.
	B6	Same as above, except 15 hrs. at 350 F after -T6 age.	"	"	"	Unforged Control	---	---
	B7	"	"	"	"	S.T.	9.3	Same as B2.
	B8	"	"	"	"	"	9.5	Same as B3.
	B9	"	"	"	"	"	16.5	Same as B4.
	B10	"	"	"	"	"	22.9	Same as B5.

TABLE V

EXPERIMENTAL PARAMETERS - THIRD PRESS FORGING OPERATION

Material Origin	Block Numbers	Heat Treatment	Block Dimensions (in.)			Forging Direction	Percent Reduction	Other Conditions
			L.	L.T.	S.T.			
7075-T651 Rolled Plate	C1	SHT at 920 F for 2 hrs., WQ,-T6 age	3.2	2.8	2.7	S.T.	20.4	Pressed in one step.
	C2	"	"	"	"	"	10.8	Same as C1
	C3	Same as C1+ 5 hrs. at 350 F	"	"	"	"	22.7	Pressed in two equal steps with water quenching after first step.
	C4	"	"	"	"	"	21.3	Same as C3
	C5	Same as C1 + 10 hrs. at 350 F (-T73 condition)	"	"	"	"	21.6	Pressed in four equal steps with water quenching after each step.
	C6	"	"	"	"	"	21.7	Same as C5
	C7	"	"	"	"	"	20.6	Precooled in liquid nitrogen. Pressed in four equal steps with quenching in liquid nitrogen after each step.
	C8	"	"	"	"	"	20.9	Same as C7

TABLE VI

EXPERIMENTAL PARAMETERS - FOURTH PRESS FORGING OPERATION

Material Origin	Block Numbers	Heat Treatment	Block Dimensions			Forging Direction	Percent Reduction	Other Conditions
			L.	L.T.	S.T.			
7075-T651 Rolled Plate	D2	SHT at 920 F for 2 hrs., WQ, -T6 age, 1 hr. at 350 F after -T6 age	3.2	2.8	2.7	S.T.	9.9	Water quenched after pressing
"	D4	Same as D2, except 2 hrs. at 350 F after -T6 age	"	"	"	"	13.2	"
"	D6	Same as D2, except 3 hrs. at 350 F after -T6 age	"	"	"	"	11.8	"
"	D8	Same as D2, except 4 hrs. at 350 F after -T6 age	"	"	"	"	12.3	"
"	D10	Same as D2, except 5 hrs. at 350 F after -T6 age	"	"	"	L.	19.6	"
"	D12	Same as D2, except 10 hrs. at 350 F after -T6 age	"	"	"	"	20.0	"

TABLE VI (Continued)

EXPERIMENTAL PARAMETERS - FOURTH PRESS FORGING OPERATION

Material Origin	Block Numbers	Heat Treatment	Block Dimensions			Forging Direction	Percent Reduction	Other Conditions
			L.	L.T.	S.T.			
7075-T73 Hand Forging	E5	SHT at 895 F for 5 hrs., WQ,-T6 age, 1 hr. at 350 F	2.6	3.0	4.1	S.T.	9.9	Water quenched after pressing
"	E7	Same as E5, except 2 hrs. at 350 F after -T6 age	"	"	"	"	10.3	"
"	E9	Same as E5, except 3 hrs. at 350 F after -T6 age	"	"	"	"	10.2	"
"	E11	Same as E5, except 4 hrs. at 350 F after -T6 age	"	"	"	"	10.2	
"	E13	Same as E5, except 5 hrs. at 350 F after -T6 age	4.0	3.0	4.1	L.	19.1	"
"	E15	Same as E5, except 10 hrs. at 350 F after -T6 age	"	"	"	"	19.4	"

from the plate, the blocks were solution treated and aged to the -T6 temper. Four of the blocks were overaged to the -T73 temper while the other four were overaged for 15 hours at 350 F. A machining step, wherein the edges and corners of the blocks were rounded off (0.250 inch radius) and the surfaces were given a smooth (RMS 63) finish, followed the heat treatment. The object of this step was to prevent large stress concentrations during forging. The machined blocks were preheated at a temperature between 325 and 350 F for 1 1/2 hours. Each set of four blocks was reduced incrementally from a thickness of about 2 5/8 to 2 1/16 inches. The forging parameters are summarized in Table III.

Tensile tests were performed in triplicate on short transverse samples taken from the center of the forged blocks. Hardness traverses were also performed in the short transverse direction of the blocks.

Operation No. 2: Overaged Tempers - Stepwise Pressing With Quenching After Each Step

The second operation differed in one important respect from the first. Preheat was not used, to minimize the tendency toward overaging (see Results-Operation No. 1). The eight starting blocks were sawed from rolled plate and had the same as-machined dimensions as the first group of blocks. Half of the blocks were in the -T73 condition while the other half had been overaged for an additional 5 hours at 350 F. The reductions, varying from 9 to 23 percent, were carried out in the short transverse

direction. An attempt was made to perform the reductions in one step, or in two, three, or four equal steps with a water quench following each step. Stepwise reduction-and-quenching was intended as a further precaution against overaging. A summary of forging parameters is contained in Table IV.

Tensile tests were conducted in triplicate on short transverse specimens taken from the center of the forged blocks. The forged blocks were sectioned and hardness traverses made in the (short transverse) direction of working.

Operation No. 3: 7075-T6 and Overaged Tempers - Stepwise Pressing With or Without Quenching After Each Step. Ambient and Cryogenic Temperatures

The eight starting blocks for this operation were in the -T6, -T73, or intermediate heat treated condition; two were in the -T6, four in the -T73, and two in the intermediate condition. All blocks originated from the -T651 rolled plate and had the same as-machined dimensions as the blocks in Operations 1 and 2. One of the -T6 blocks was reduced by ~10 percent. Otherwise the reductions amounted to ~20 percent. All reductions were made in the short transverse direction.

The two -T6 blocks were pressed in one step, without water quenching, in an attempt to induce some overaging. The two intermediate heat treated blocks were pressed in two equal steps, with water quenching after the first step only, to induce somewhat less overaging. Two of the four -T73 blocks were pressed in four equal steps, with water quenching after each step, to minimize or eliminate overaging. These blocks were pressed at room temperature. The remaining two -T73 blocks were pressed after a

precooling treatment in liquid nitrogen, the object being to obtain greater work hardening at the lower temperature. The full reduction was accomplished in four equal steps with cooling in liquid nitrogen following each step. The forging parameters for this operation are summarized in Table V.

Tensile tests were conducted in duplicate on short transverse specimens from each of the forged blocks and on longitudinal specimens from those blocks in the intermediate heat treated condition. These specimens were centrally located with respect to the short transverse and longitudinal dimensions of the blocks, respectively. Alternate immersion stress-corrosion tests were conducted on short transverse specimens from each of the forged blocks as well as from the as-received -T651 plate. These tests were conducted in duplicate at 75 percent of the yield strength. Additional stress-corrosion tests were conducted on short transverse specimens from the intermediate heat treated-and-forged material at applied stress levels of 25 and 35 psi. The object of these tests was to determine the threshold stress for cracking. Hardness traverses were carried out in the short transverse direction, as in the previous two operations.

Material was taken from one of the upset 7075-T6 blocks (C2) and overaged for 20 min., 40 min., 1 hr., 2 hr., or 3 hr. at 350 F. Short transverse tensile and stress-corrosion specimens were machined and tested.

Operation No. 4: Overaged Tempers - Comparison of Different Starting Forms and Pressing Directions

The fourth and last in the present series of press forging operations was carried out on (12) 7075 aluminum blocks. Half of these blocks originated from -T651 rolled plate and the other half from -T73 hand forgings. The blocks were solution treated, aged to the -T6 temper, and finally overaged at 350 F for times varying from 1 to 10 hours. Those blocks which had been overaged for 1 to 4 hours were reduced by ~10 percent in the short transverse direction, and the blocks which had been overaged for 5 or 10 hours were given a larger reduction (~20%) in the longitudinal direction. The object of the longitudinal reduction was to determine if exceptional short transverse strengthening could be obtained. A summary of parameters for this operations is presented in Table VI.

Tensile tests were conducted in duplicate on short transverse specimens machined from the center of the unforged control blocks and of the forged blocks. Additional tensile tests were performed on longitudinal specimens from those forged blocks possessing short transverse yield strengths in excess of 70,000 psi. Stress-corrosion tests were conducted on short transverse specimens from the same forged blocks (i.e., with short transverse yield strengths exceeding 70,000 psi) and on specimens from the unforged control blocks.

The press forged material originating from rolled plate and having a short transverse yield strength of 70,000 psi or more was given a short (1/4 or 1/2 hour) overaging treatment at 350 F. Tensile and stress-corrosion specimens were machined from the overaged material and tested. The stress-corrosion tests were conducted at 75% of the yield strength.

Hardness traverses were carried out not only in the short transverse but also in the longitudinal direction for the D and E series of blocks. Specifically, the following blocks were examined: D1, D2, D11, D12; E4, E5, E14, E15.

RESULTS

EXPLORATORY HEAT TREATMENT

The hardness and x-ray results are summarized in Table VII. Interrupted aging under the selected experimental conditions had an insignificant effect on the measured properties. With short ($\leq$3 hrs.) artificial aging times (Sample No. 6, Table VII), hardnesses comparable with that of 7075-T6 and particle sizes comparable with that of 7075-T73 were obtained. This very rapid growth of η particles is somewhat surprising. Comparable volume fractions with respect to -T73 were not obtained until longer ($\sim$10 hrs.) aging times.

An average yield strength of 66,600 psi was obtained from three tensile tests, which is the same as the short transverse value for the as-received 7075-T651 plate (67,000 psi). The stress-corrosion resistance seemed to be significantly better, however, for the experimental material. The times-to-failure of three specimens loaded to 75% of the yield strength varied from 10 to 17 days, compared to 1 to 3 days for the as-received material (four specimens).

TABLE VII

HARDNESS AND X-RAY RESULTS OBTAINED FROM EXPLORATORY HEAT TREATMENT

Sample No.	Heat Treatment	Hardness (Superficial Rockwell, 30-T)	Integral Breadth η Phase*	Relative Intensity η Phase **
1	SHT 895F, WQ, 23 hr. natural age, 6 hr. age at 350 F.	73.0	0.015	0.56
2	Same as Sample No. 1, except 41 hr. interruption after 350 F age, followed by additional 4 hr. age at 350 F.	70.8	0.012	0.87
3	Same as Sample No. 2, except interruption followed by additional 13 hr. age at 350 F.	68.5	0.013	1.03
4	Same as Sample No. 1, except 209 hr. interruption after 350 F age, followed by additional 4 hr. age at 350 F.	71.0	0.012	0.81
5	Same as Sample No. 4, except interruption followed by additional 13 hr. age at 350 F.	68.6	0.013	1.1
6	Same as Sample No. 1, except 3 hr. age at 350 F after natural age.	75.3	0.012	0.60
7	Same as Sample No. 1, except 11 hr. age at 350 F after natural age.	71.0	0.013	1.04
8	Same as Sample No. 1, except 19 hr. age at 350 F after natural age.	69.1	0.012	0.97
9	7075-T73	69.3	0.012	0.90

*Measure of η-phase particle size.
**Measure of volume fraction of η phase.

PRESS FORGING

Operation No. 1

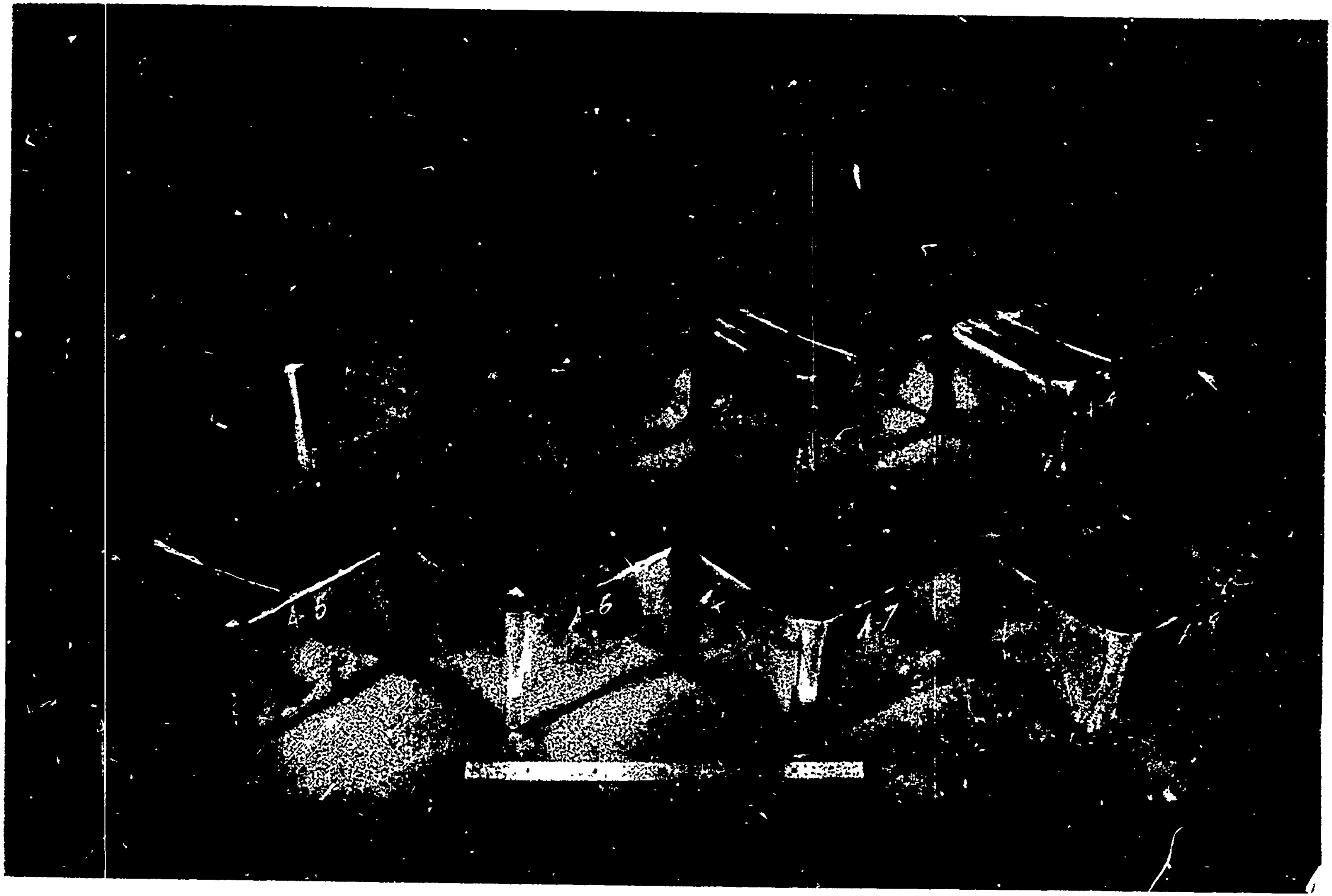
A photograph of the press forged blocks is shown in Fig. 1. No cracking occurred in any of the blocks.

The tensile results are summarized in Table VIII. A comparison of the results obtained from the forged blocks with those obtained from the unforged control blocks (B1 and B6, see Table IX) indicates a decrease in the strength and hardness properties instead of the expected increase. Thus either recrystallization or overaging had taken place as a result of the warm working. A light microscopic examination revealed no difference between the worked and unworked material, leading to the conclusion that overaging was the correct explanation for the lower properties. (Preheat was omitted and stepwise reduction and quenching were used in the second forging operation to minimize overaging.)

The results of the hardness traverses are shown in Fig. 2. No gradients between the surface and center of the blocks were found.

Operation No. 2

A photograph of the pressed blocks is shown in Fig. 3. No cracks were observed in any of the blocks.



5AG25-6/27/69-C1

Figure 1. "A" Series of Blocks Press Forged in Operation No. 1.

TABLE VIII

TENSILE PROPERTIES OBTAINED (IN TRIPLICATE) FOR SHORT TRANSVERSE

SPECIMENS MACHINED FROM "A" SERIES OF BLOCKS (PRESS FORGING OPERATION NO. 1)

Block No.	Yield Strength (psi)		Ultimate Strength (psi)		% Elongation ($\frac{1}{2}$-in. G. L.)	
A1	49,590		58,680		4.0	
	52,230	51,890	64,050	62,420	5.0	4.7
	53,850		64,530		5.0	
A2	50,340		59,660		6.0	
	49,610	49,850	58,660	59,230	6.0	6.0
	49,590		59,350		6.0	
A3	50,250		59,660		6.0	
	49,230	49,690	59,300	59,030	6.0	6.0
	49,590		58,130		6.0	
A4	50,810		58,130		6.0	
	51,630	50,550	58,540	58,220	6.0	5.7
	49,200		58,000		5.0	
A5	47,170		58,270		6.0	
	47,240	47,680	57,090	57,960	6.0	6.0
	48,620		58,540		6.0	
A6	48,780		48,780		-	
	47,240	47,760	56,690	54,190	6.0	6.0
	47,240		57,090		6.0	
A7	47,240		57,090		6.0	
	48,430	47,910	57,870	57,570	6.0	6.0
	48,060		57,750		6.0	
A8	47,240		56,690		6.0	
	47,840	47,670	56,000	56,360	6.0	6.0
	47,920		56,400		6.0	

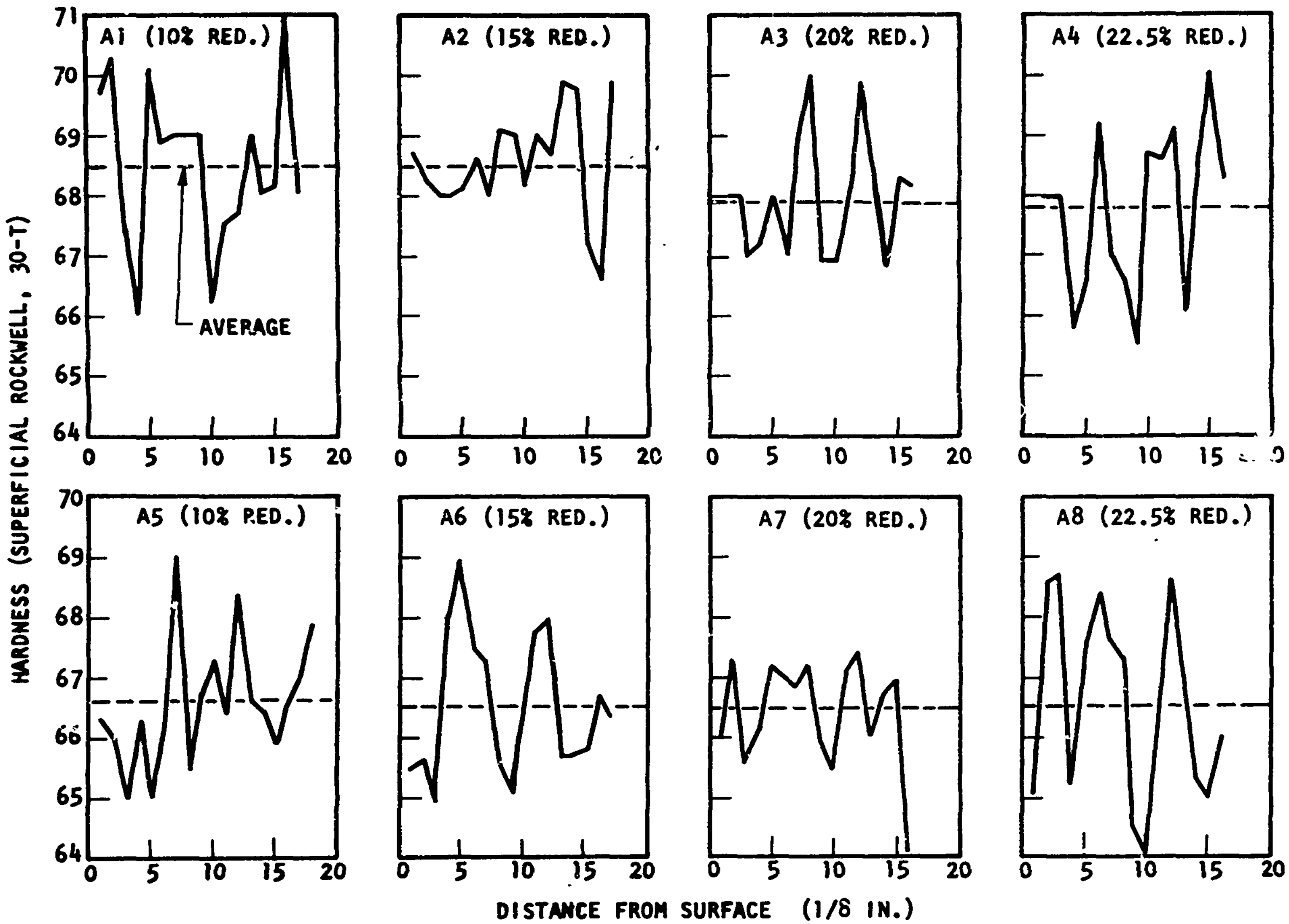
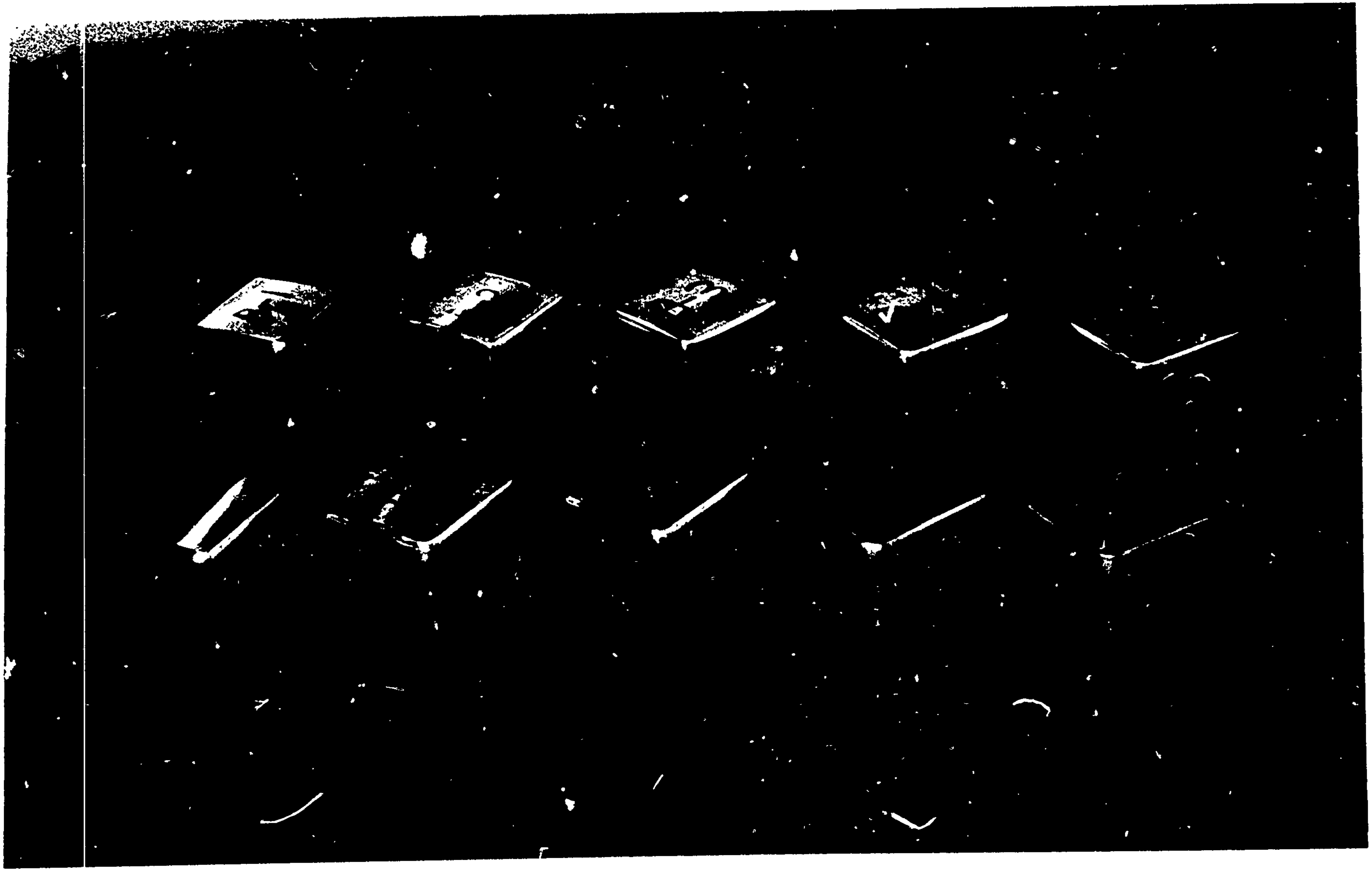


Figure 2. Results of Hardness Traverses Over the Short Transverse Thickness of "A" Series of Blocks.



5AG15-8/14/69-C1

Figure 3. "B" Series of Blocks Press Forged in Operation No. 2.

The tensile test results (Table IX) indicated that overaging had not occurred. Yield strength increments (as measured halfway through the short transverse thickness) varied from ~3 to 5 ksi in the -T73 specimens and from ~0 to 3 1/2 ksi in the specimens which had been overaged for 15 hours at 350 F. In the most favorable case, the yield strength had increased from 54,000 to 59,000 psi. Because the latter value was still below the desired level (70,000 psi), stress-corrosion tests were not conducted.

Whether a given reduction was accomplished in one step or in two equal steps, with quenching after each step, seemed to have little or no effect on strengthening (cf. results for B2 and B3 and for B7 and B8, Table IX). Increasing the amount of reduction from 9 to 23 percent also had no significant effect on the strength increment.

The results of the hardness traverses are shown in Fig. 4. No gradients between the surface and center of the blocks were observed except in the case of the unpressed control blocks, B1 and B6, where the hardness fell below average in the middle of the blocks.

Operation No. 3

A photograph of the blocks taken after pressing is shown in Fig. 5. The only block that showed any cracking was C1. This block, which was in the -T6 condition, had received a 20 percent reduction.

TABLE IX

TENSILE PROPERTIES OBTAINED (IN TRIPLICATE) FOR SHORT TRANSVERSE SPECIMENS MACHINED FROM "B" SERIES OF BLOCKS (PRESS FORGING OPERATION NO. 2)

Block No.	Yield Strength (psi)		Ultimate Strength (psi)		% Elongation (1/2-in. G.L.)	
B1 (Control)	54,470 54,200 54,000	54,230	64,230 64,450 63,760	64,150	4.0 4.0 4.0	4.0
B2	57,080 57,320 57,870	57,400	67,260 68,290 68,110	67,890	2.0 2.0 3.0	2.3
B3	57,980 58,130 58,000	58,040	66,980 67,480 68,000	67,490	2.0 3.0 2.0	2.3
B4	57,870 56,980 58,800	57,880	67,320 66,050 67,200	66,860	3.0 2.0 2.0	2.3
B5	59,060 58,800 58,260	58,710	68,900 67,600 67,520	68,010	2.0 2.0 2.0	2.0
B6 (Control)	54,880 54,550 54,710	54,710	63,980 64,050 64,710	64,250	4.0 4.0 4.0	4.0
B7	57,480 58,260 58,540	58,090	67,720 67,770 68,290	67,930	2.0 3.0 2.0	2.3
B8	55,690 54,870 53,540	54,700	65,040 64,780 64,170	64,660	3.0 3.0 3.0	3.0
B9	56,610 55,690 54,960	55,750	60,740 63,980 64,630	63,120	1.0 2.0 2.0	1.7
B10	57,320 56,300 55,370	56,330	64,880 65,290 64,460	64,880	2.0 2.0 2.0	2.0

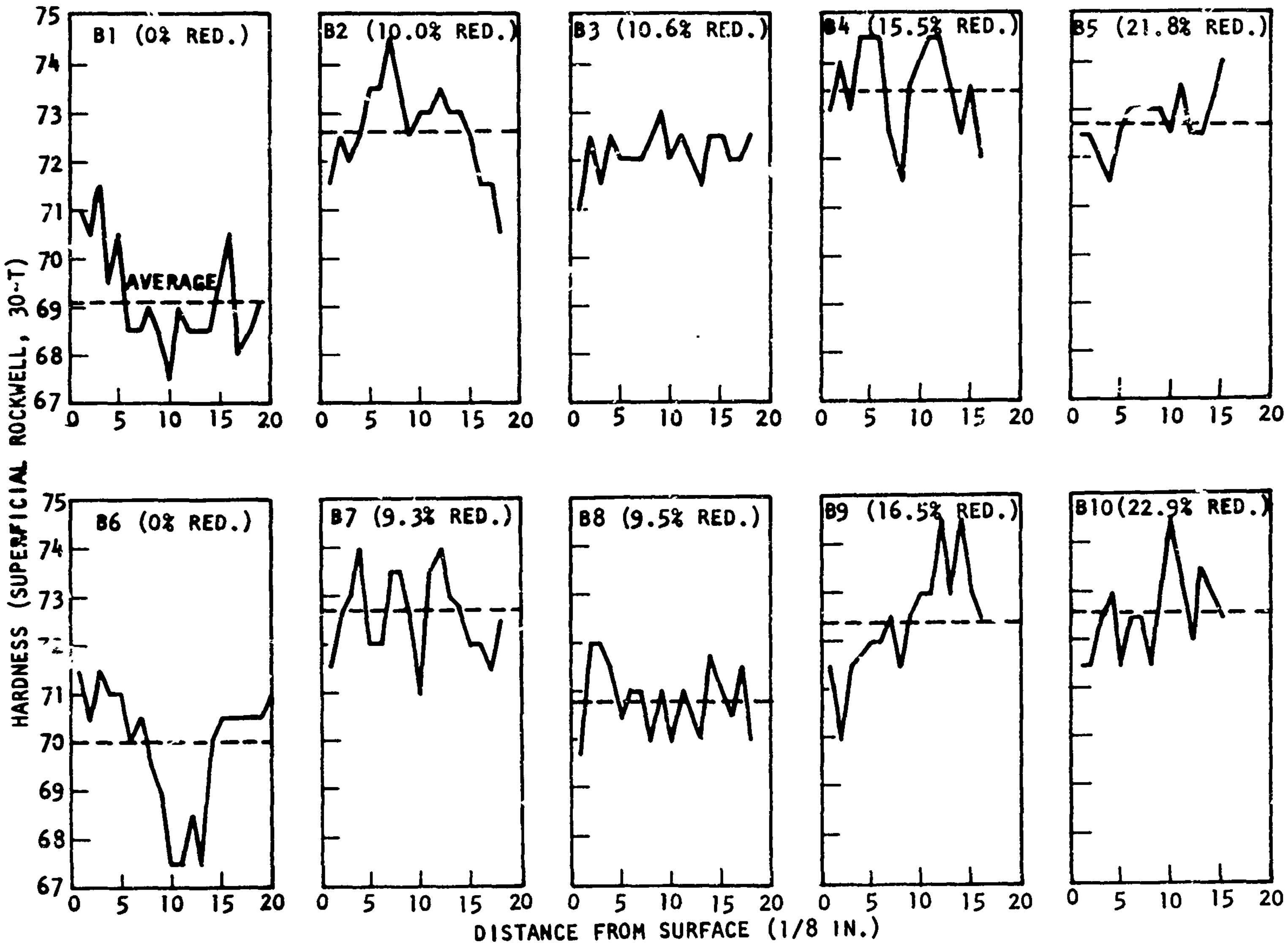


Figure 4. Results of Hardness Traverses Over the Short Transverse Thickness of "B" Series of Blocks.

5AG16-9/12/69-C1

Figure 5. "C" Series of Blocks Press Forged in Operation No. 3.

The results of tensile tests (Table X) indicated that the yield strength of the 7075-T6 blocks had been increased by ~7,000 psi (compared to the value for the as-received -T651 plate) to 74,000 psi; the intermediate heat treated blocks had been strengthened to the as-received -T651 level; and the -T73 blocks had been strengthened by ~6,000 psi, from 54,000 (Bl value) to 60,000 psi. The stepwise reduction-and-quenching sequences and the precooling in liquid nitrogen had no apparent effect on the final strength properties.

The results of alternate immersion stress-corrosion tests conducted on duplicate specimens from each of the forged blocks in the C-series are shown in Table XI. The results obtained for specimens machined directly from the as-received -T651 plate are shown for comparison. The most striking result is that the intermediate heat treatment followed by upsetting gave a substantial increase in stress-corrosion lifetime, at no sacrifice in yield strength, compared to the as-received -T651 plate.

The results of the longitudinal tensile tests and of the 25 and 35 ksi short transverse stress-corrosion tests are shown in Tables XII and XIII respectively. These tests were conducted on intermediate heat treated/upset material because the properties reported above appeared so promising.

As indicated in Table XII, an exceptionally high longitudinal yield strength (80,600 psi), compared to the short transverse yield strength (66,000 psi), was obtained by press forging in the short transverse direction. The

TABLE X

TENSILE PROPERTIES OBTAINED (IN DUPLICATE) FOR SHORT TRANSVERSE SPECIMENS MACHINED FROM "C" SERIES OF BLOCKS (PRESS FORGING OPERATION NO. 3)

Block No.	Yield Strength (psi)		Ultimate Strength (psi)		% Elongation (1/2-in. G.L.)	
C1	73,660 74,420	74,040	83,970 84,730	84,350	2.0 2.0	2.0
C2	74,400 74,400	74,400	86,000 86,800	86,400	2.0 1.5	1.8
C3	65,750 66,370	66,060	74,570 78,320	76,440	2.0 2.0	2.0
C4	65,450 67,200	66,320	72,680 74,000	73,340	1.5 1.5	1.5
C5	60,330 59,350	59,840	68,600 67,640	68,120	2.0 2.0	2.0
C6	60,510 59,240	59,880	68,970 68,070	68,520	2.0 2.0	2.0
C7	59,500 61,350	60,430	68,350 69,080	68,710	2.0 2.0	2.0
C8	59,500 59,500	59,400	66,280 67,930	67,110	2.0 2.0	2.0
C0 (Control) (As-Received)	67,480 66,800	67,140	77,890 78,000	77,940	2.5 2.5	2.5

TABLE XI

RESULTS OF ALTERNATE IMMERSION STRESS-CORROSION TESTS

(IN DUPLICATE) ON SPECIMENS IN FOUR HEAT TREATED CONDITIONS.

APPLIED STRESS WAS 75% OF YIELD STRENGTH

Heat Treated Condition	Block No.	Yield Strength (psi)	Time-to-Failure (days)
7075-T651 (as-received rolled plate, 2 3/4-in. thick)	C0	67,140	4 1
7075-T6	C1	74,040	3 3
	C2	74,400	3 1
Intermediate	C3	66,060	23 30
	C4	66,320	33 33
7075-T73	C5	59,840	30 64 1/2
	C6	59,880	69 36
	C7 (pre-cooled liq.N)	60,430	54 50 1/2
	C8 (pre-cooled liq.N)	59,500	48 30

TABLE XII

LONGITUDINAL TENSILE PROPERTIES OF INTERMEDIATE

HEAT TREATED/UPSET 7075 ALUMINUM

Block No.	Specimen No.	Yield Strength (psi)		Ultimate Strength (psi)		% Elongation (1/2-in. G.L.)	
C3	1	78,050		81,300		8.0	
	2	82,110	80,600	84,960	83,200	10.0	8.7%
	3	81,620		83,330		8.0	

TABLE XIII

RESULTS OF SHORT TRANSVERSE STRESS-CORROSION TESTS

CONDUCTED ON INTERMEDIATE HEAT TREATED/UPSET

MATERIAL AT APPLIED STRESS LEVELS OF 25 AND 35 KSI

Block No.	Specimen No.	Applied Stress (ksi)	Time-to-Failure (days)
C3	1	35	43
	2	35	79
	3	25	119 (NF)
	4	25	119 (NF)

longitudinal ductility (8.7% elongation) was also high compared to the short transverse ductility (2.0% elongation).

The results shown in Table XIII indicate that the threshold stress for cracking in the intermediate heat treated/upset material lies between 25 and 35 ksi. Numerous further tests would be required to substantiate this conclusion. No attempt was made to determine the threshold for the as-received -T651 plate. A threshold stress of 7 ksi has been reported by Alcoa personnel (Ref. 7), as a result of 103 tests performed on short transverse specimens from 7075-T6 plate.

The tensile and stress-corrosion properties of the upset/overaged 7075-T6 (Block No. C2) are presented in Tables XIV and XV. None of the five groups of specimens had as good a combination of properties as the intermediate heat treated/pressed material.

The results of the hardness traverses are shown in Fig. 6. No gradients were found.

Operation No. 4

A photograph of the press forged blocks is shown in Fig. 7. One fine crack was observed in each of Blocks D4 and D8 (not apparent in photograph); several cracks were found in Blocks D10 (Fig. 7) and D12 (not apparent in photograph). The cracks did not interfere with specimen preparation.

TABLE XIV

SHORT TRANSVERSE YIELD STRENGTH PROPERTIES OF UPSET/OVERAGED 7075-T6

Overaging Time at 350 F (hr)	Specimen No.	Yield Strength (psi)	Av. Yield Strength (psi)
1/3	40	67,480	67,460
	41	67,440	
2/3	50	69,110	69,000
	51	68,900	
1	10	63,180	64,270
	11	65,350	
2	20	60,000	59,800
	21	59,600	
3	30	58,660	58,720
	31	58,780	

TABLE XV

STRESS-CORROSION TIME-TO-FAILURE DATA FOR UPSET/OVERAGED 7075-T6 SPECIMENS STRESSED TO 75% OF YIELD STRENGTH IN SHORT TRANSVERSE DIRECTION

Overaging Time at 350 F (hr)	Specimen No.	Time-to-Failure (days)
1/3	42	5
	43	1
2/3	52	2
	53	3
1	12	NF in 30 days
	13	14
2	22	NF in 30 days
	23	NF in 30 days
3	32	NF in 30 days
	33	NF in 30 days

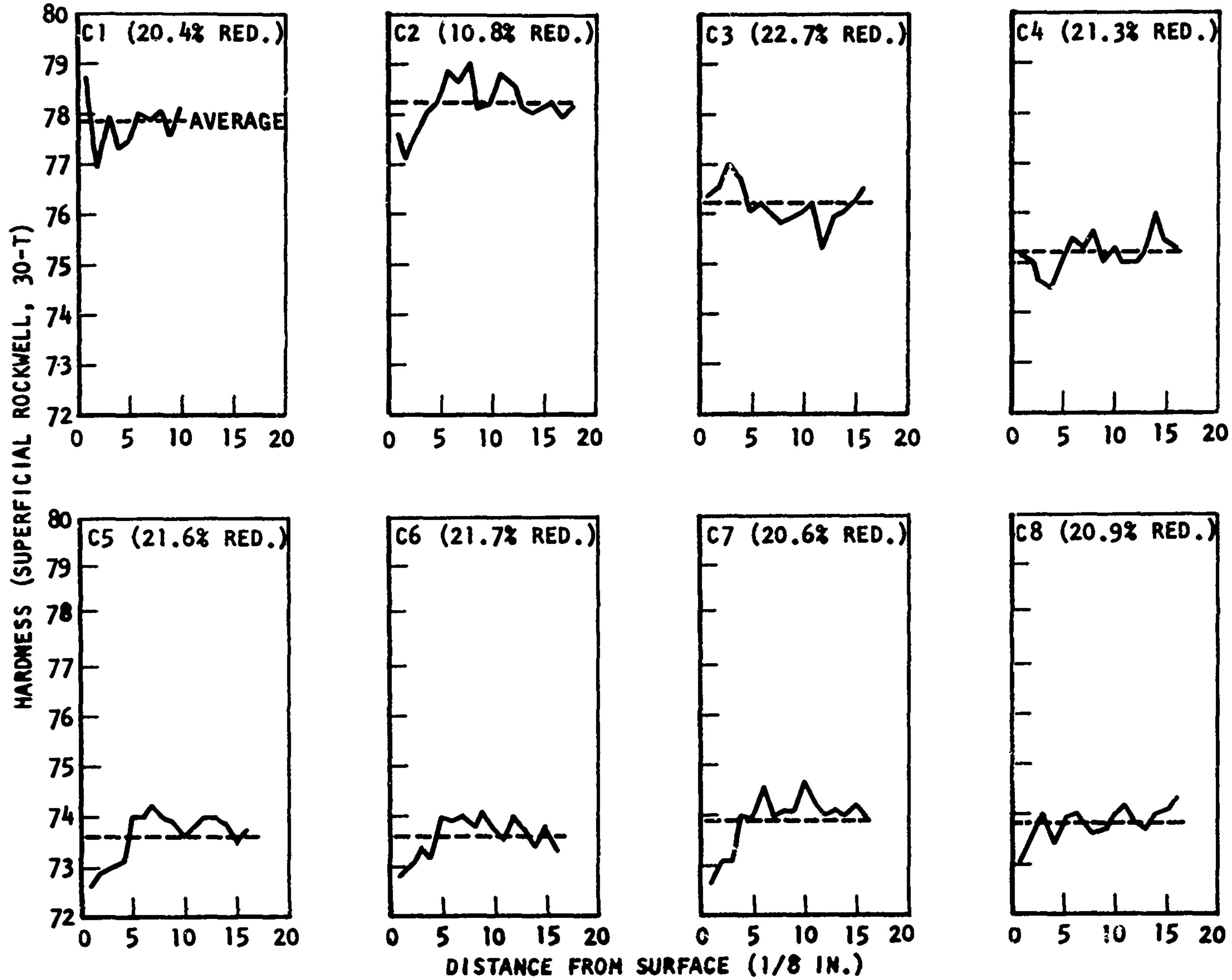
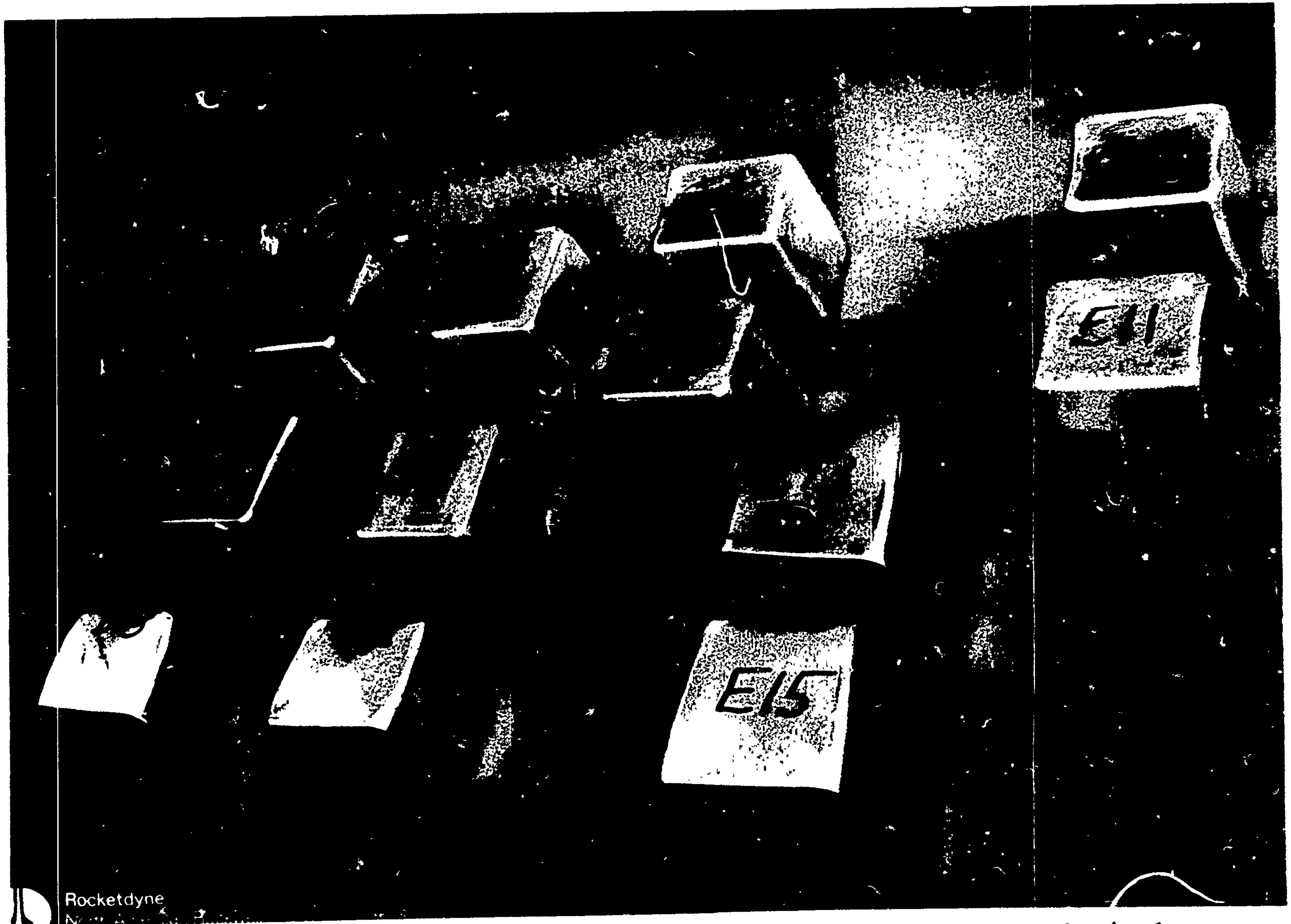


Figure 6. Results of Hardness Traverses Over the Short Transverse Thickness of "C" Series of Blocks.



5AG46-12/17-69-C1

Figure 7. "D" and "E" Series of Blocks Press Forged in Operation No. 4.

The results of tensile tests conducted on short transverse specimens, which had been machined from the forged blocks and the unforged control blocks, are shown in Fig. 8. The desired yield strength of 70,000 psi or better was attained in material which had been overaged for 1 hour (rolled and forged stock) and upset in the short transverse direction; and also in material which had been overaged for 5 or 10 hours (rolled and forged stock) and upset in the longitudinal direction. These results are summarized in Table XVI. This table also contains the results obtained for longitudinally oriented specimens.

It was found in Operation No. 3 that if a rolled plate of 7075 is press forged in the short transverse direction, the degree of strengthening is considerably higher in the longitudinal direction (perpendicular to short transverse direction) than in the short transverse direction. This result is re-presented in Table XVI. At the same time, the short transverse ductility is more adversely affected than the longitudinal ductility (Table XVI). Conversely, if a rolled plate or a hand forging of 7075 is press forged in the longitudinal direction, the resultant strengthening in the short transverse direction is unusually high (10,500-13,400 psi), and, for the rolled plate only, there is no deleterious effect on the short transverse ductility. It is interesting to note that the longitudinal yield strength of the rolled plate actually decreases.

The stress-corrosion results are summarized in the graphs of Fig. 9 and 10, for rolled plate and hand forgings, respectively. Time-to-failure (t_f) is shown plotted as a function of overaging treatment. The following two

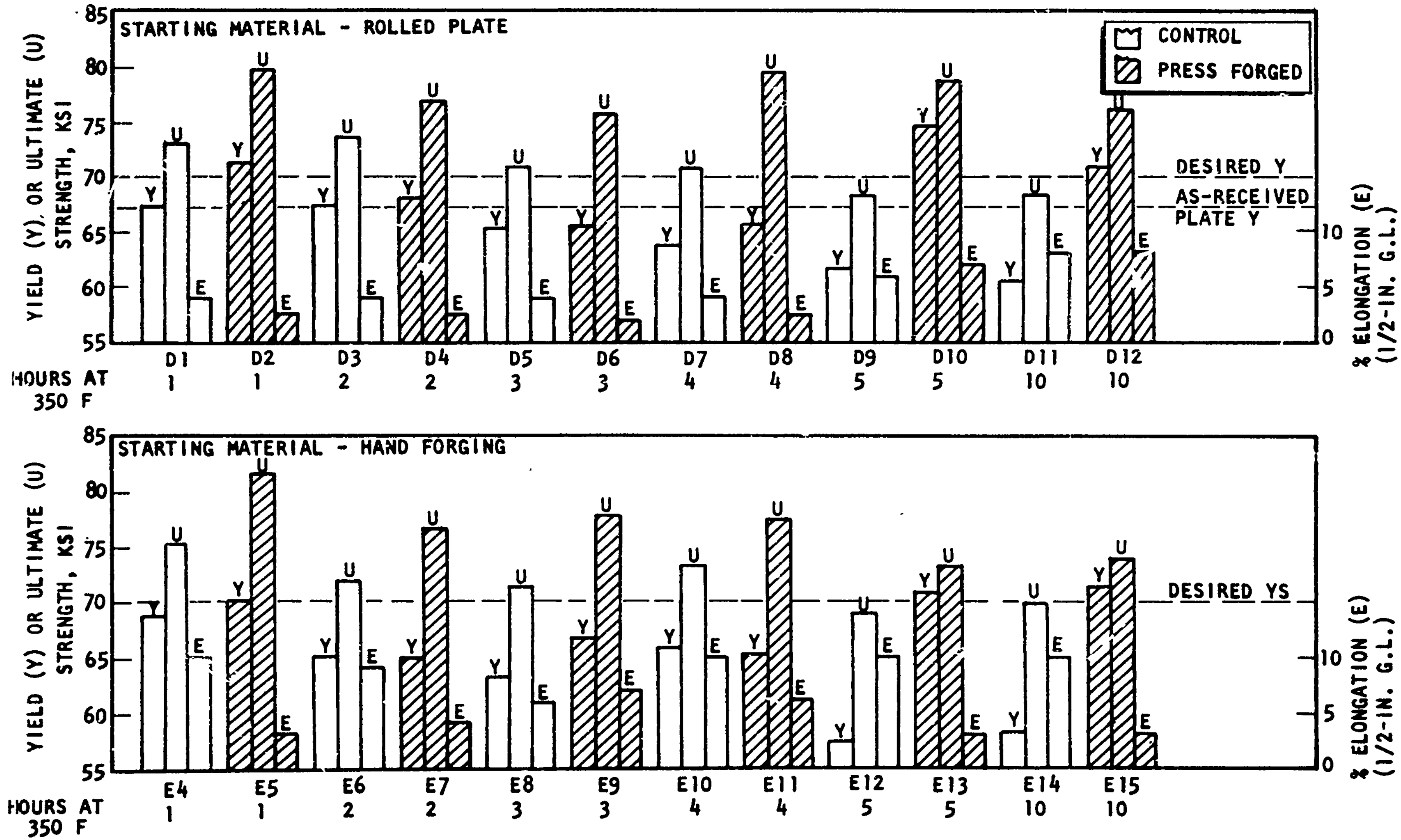


Figure 8. Tensile Properties of "D" and "E" Series of Blocks.

TABLE XVI

CHANGE IN YIELD STRENGTH AND ELONGATION OF 7075 ALUMINUM

AS A FUNCTION OF PRESS FORGING DIRECTION AND SPECIMEN ORIGIN

Block No.	Prior Heat Treatment	Origin of Block	Direction of Press Forging*	Yield Strength (Y.S.) (psi) Short Transverse (S.T.)	Longitudinal (L.)	Increase in Y.S. (psi) S.T.	L.	% Elongation (1/2-in. G.L.) S.T.	L.	Change in % Elongation S.T.	L.
D9	-T6+ 5 hrs. at 350F	Rolled Plate	Unworked Control	61,500	67,135	--	--	6.0	12.0	--	--
C3	"	Rolled Plate	S.T.	66,100	80,600	4,600	17,100	2.0	8.7	-4.0	-3.3
D10	"	Rolled Plate	L.	74,600	62,295	13,100	-4,840	7.0	11.5	+1.0	-0.5
D11	-T6+ 10 hrs. at 350F	Rolled Plate	Unworked Control	60,400	64,035	--	--	8.0	12.0	--	--
D12	"	Rolled Plate	L.	70,900	61,460	1[illegible],500	-2,575	8.0	11.5	0	-0.5
E12	-T6+ 5 hrs. at 350F	Hand Forging	Unworked Control	57,500	65,415	--	--	10.0	13.0	--	--
E13	"	Hand Forging	L.	70,900	68,690	13,400	3,275	3.0	11.0	-7.0	-2.0
E14	-T6+ 10 hrs. at 350F	Hand Forging	Unworked Control	58,200	64,350	--	--	10.0	13.0	--	--
E15	"	Hand Forging	L.	71,400	68,855	13,200	4,505	3.0	9.0	-7.0	-4.0

* All blocks given 20% reduction, no subsequent thermal treatment

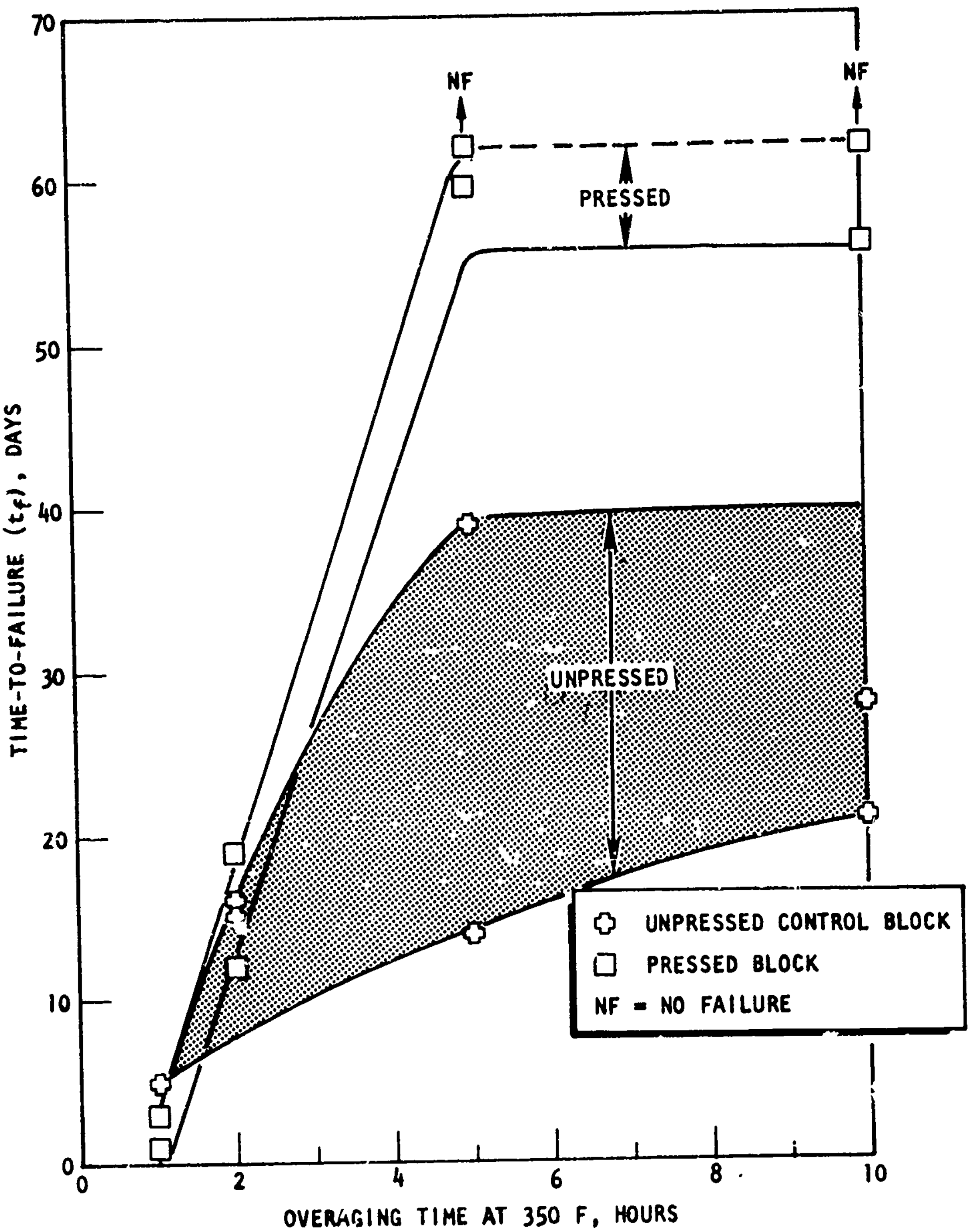


Figure 9. Stress-Corrosion Lifetime of "D" Series of Blocks.

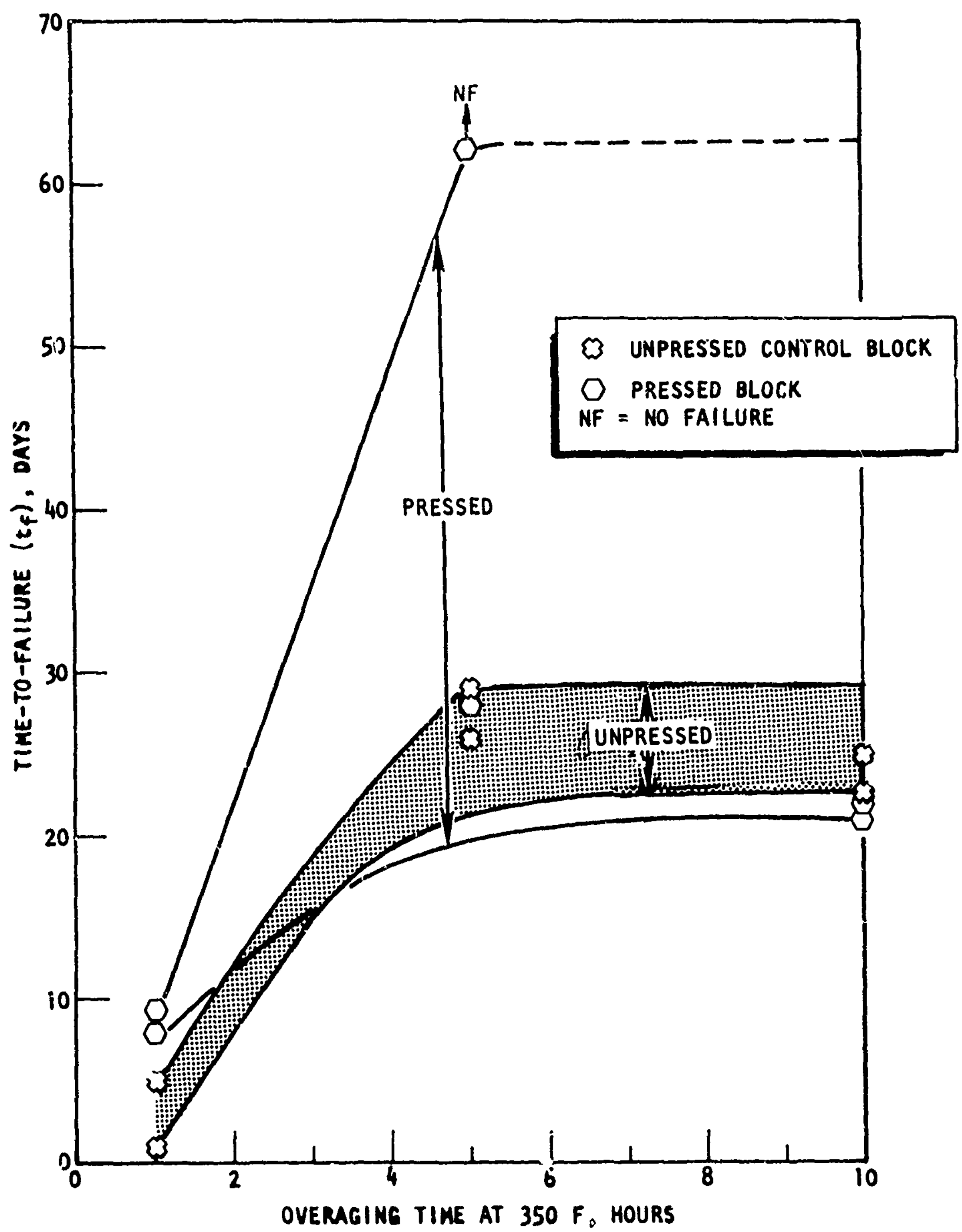


Figure 10. Stress-Corrosion Lifetime of "E" Series of Blocks.

conclusions can be drawn from the graphs: (1) t_f increases with overaging time up to an overaging time of 5 hours and then levels off or decreases, for both pressed and unpressed material, and (2) there is no significant difference in the stress-corrosion performance of pressed and unpressed material, except in the case of rolled plate which has been overaged for 5 or 10 hours at 350 F, where the pressed material has from 2 to 3 times the lifetime of the unpressed material. Thus, the press forged material has at least as high, or better, stress-corrosion resistance than the unpressed 7075-T73 or other overaged material.

The changes in yield strength as a result of overaging Blocks D2, D10, and D12 are shown in Table XVII; the corresponding times-to-failure appear in the last column of the same table. The yield strength of Block D2 is observed to decrease monotonically with overaging time. Following an initial decrease in the yield strength of Blocks D10 and D12, this property increases with overaging time after an overaging time of 1/4 hour. The significance of this increase is uncertain. Overaging D10 and D12 has effected a slight increase in an elongation value that was already relatively high and the stress-corrosion resistance is also observed to remain high.

The results of the hardness traverses are plotted in Figs. 11 and 12. Hardness troughs, in which the hardness values fall below the average value, are observed in the center of Blocks D1, D11, E4, and E14, i.e., the unpressed control blocks. Except in the case of Block D12, the hardness troughs are eliminated by the pressing operation.

TABLE XVII

TENSILE AND STRESS-CORROSION PROPERTIES OF PRESS FORGED BLOCKS D2, D10, AND D12, AFTER AN OVERAGING TREATMENT OF 350 F AS INDICATED

Block No.	Time at 350F (hr.)	Specimen No.	Yield Strength (psi)		% Elongation (1/2-in. G.L.)		Specimen No.	Time-to-Failure (days)
D2	0	25	70,090	71,390	2.0	2.5		
		26	72,690		3.0			
							27	1
							28	3
	1/4	47	66,940	67,130	3.0	2.5		
		48	67,320		2.0			
							45	4
							46	1
	1/2	51	65,950	64,525	2.0	2.0		
		52	63,100		2.0			
							49	8 1/2
							50	7
D10	0	41	74,400	74,595	7.0	7.0		
		42	74,790		7.0			
							43	NF (61)*
							44	59 1/2
	1/4	55	65,040	65,855	9.0	8.5		
		56	66,670		8.0			
							53	NF (38)
							54	"
	1/2	59	66,690		8.0			
							57	"
							58	"
D12	0	45	70,730	70,935	8.0	8.0		
		46	71,140		8.0			
							47	NF (61)
							48	"
	1/4	62	63,030	62,925	9.0	9.0		
		63	62,820		9.0			
							60	NF (38)
							61	"
	1/2	66	66,450		8.0			
							64	"
							65	"

* No failure in 61 days

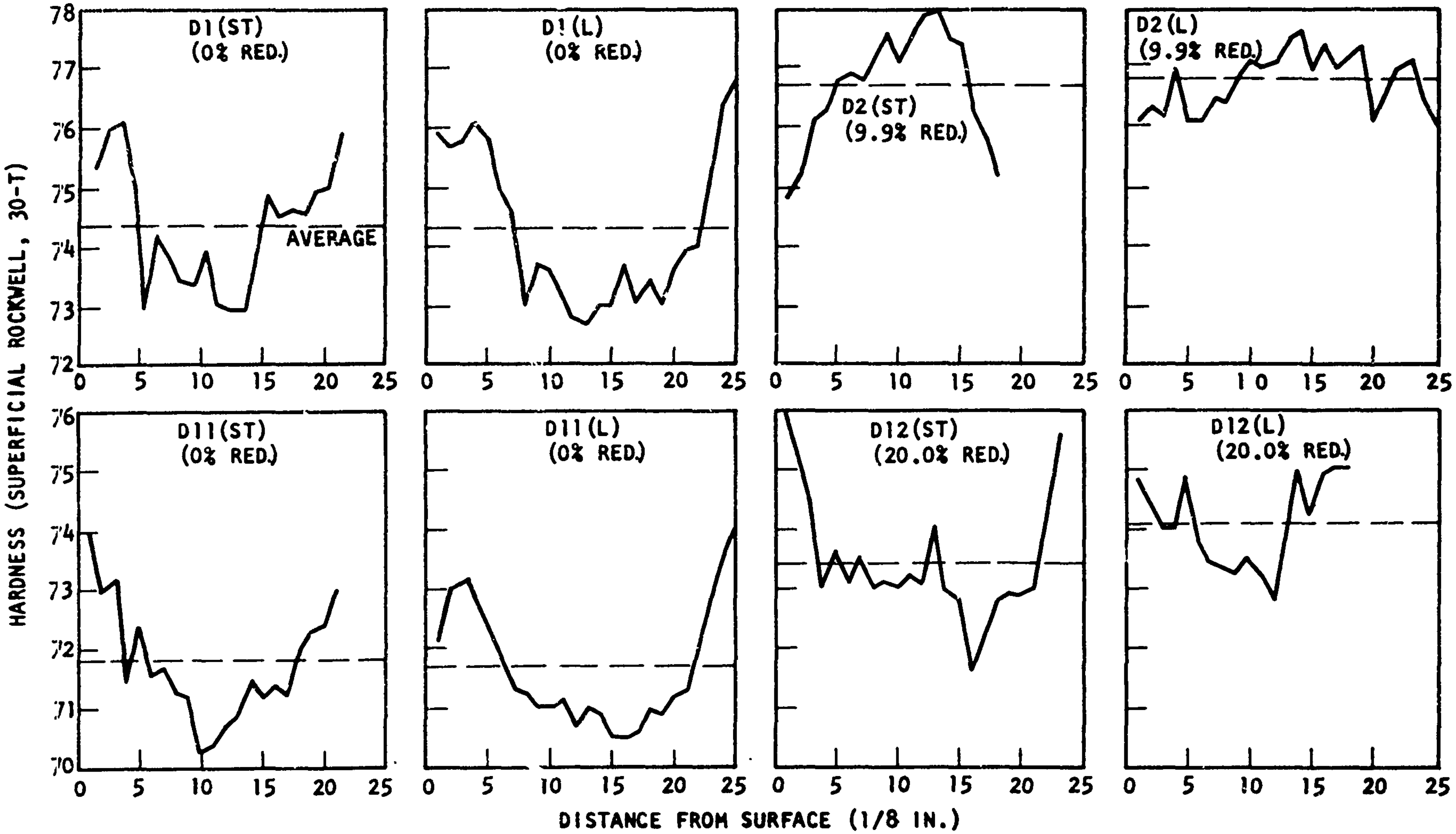


Figure 11. Results of Short Transverse (ST) and Longitudinal (L) Hardness Traverses for Selected "D" Series Blocks.

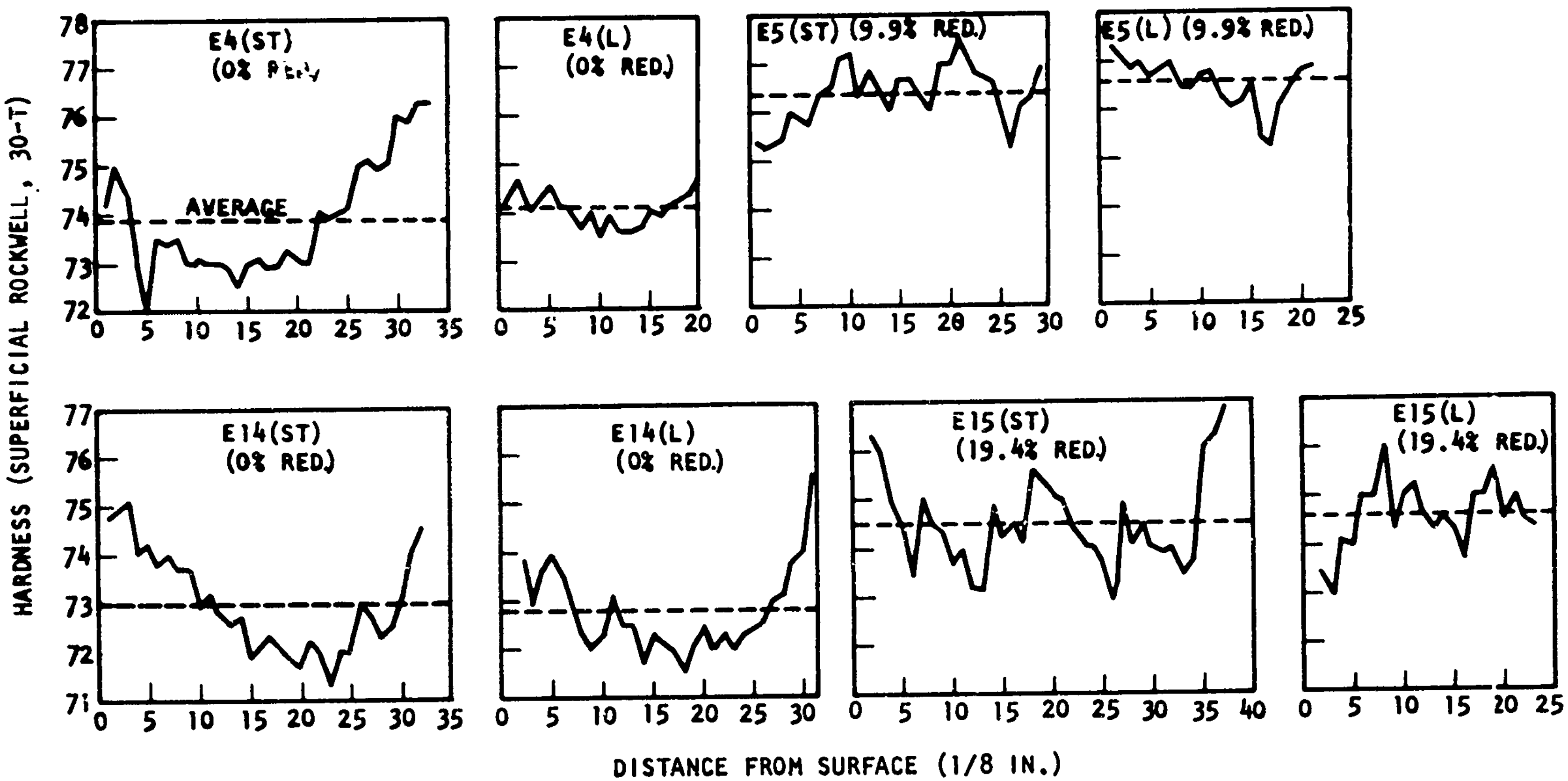


Figure 12. **Results** of Short Transverse (ST) and Longitudinal (L) Hardness Traverses for Selected "E" Series Blocks.

A composite light micrograph of Block D10 is shown in Fig. 13. Comparison of the microstructure with that of the as-received plate reveals that extensive changes have resulted from the 20% longitudinal reduction. The morphological transformations that have occurred in the "B" and "C" planes are consistent with the excellent short transverse properties (tensile and stress-corrosion) of the press-forged block. The predominant grain orientation in plane "C" is observed to be parallel to the short transverse direction of this block. It is recognized that each of the three micrographs shown in Fig. 13b is representative of a single location in Block D10. Additional metallography would be required to establish any dependence of microstructure on position in the block.

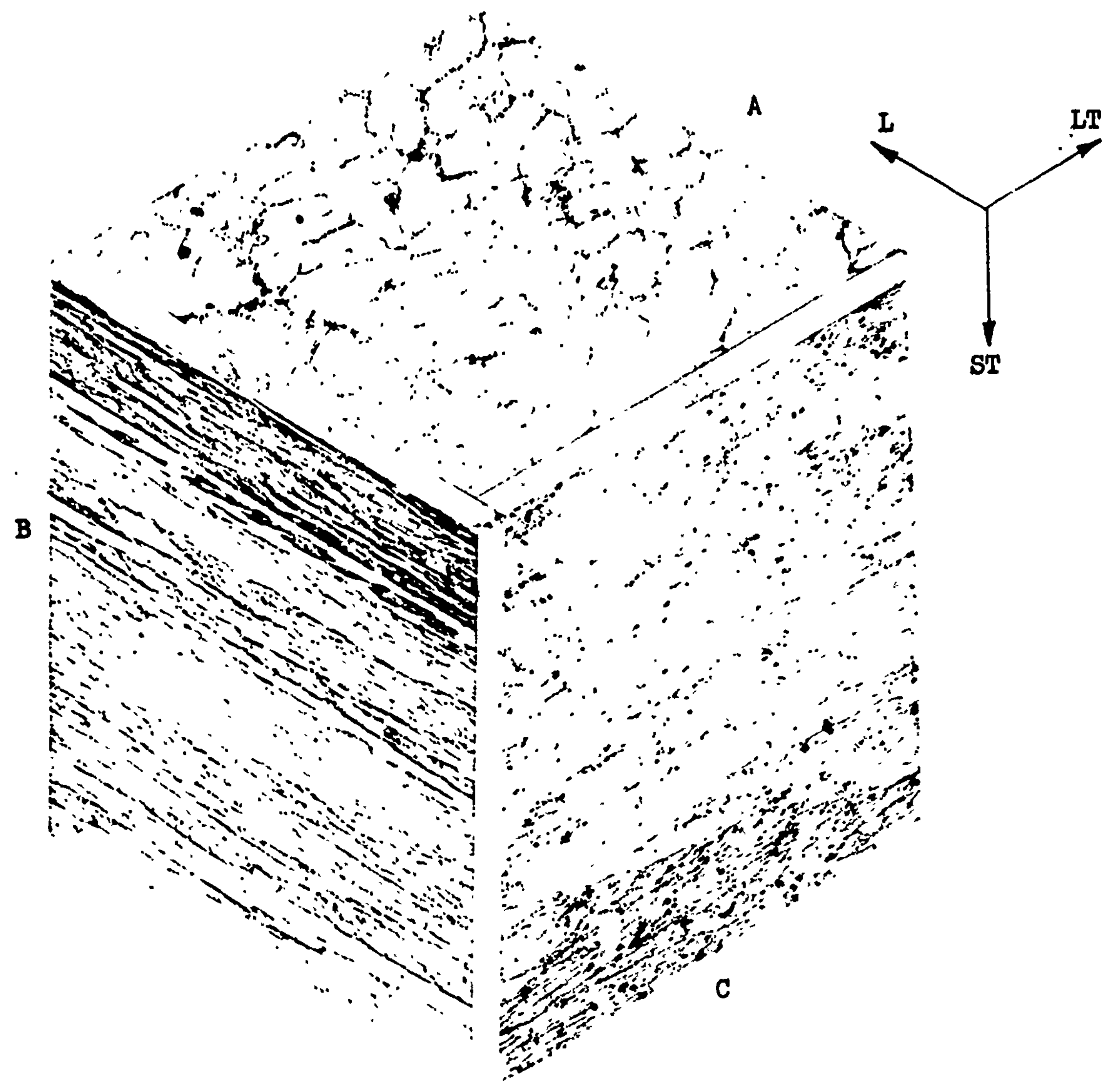


Figure 13a. Light Micrograph of As-Received 7075-T651 Plate.

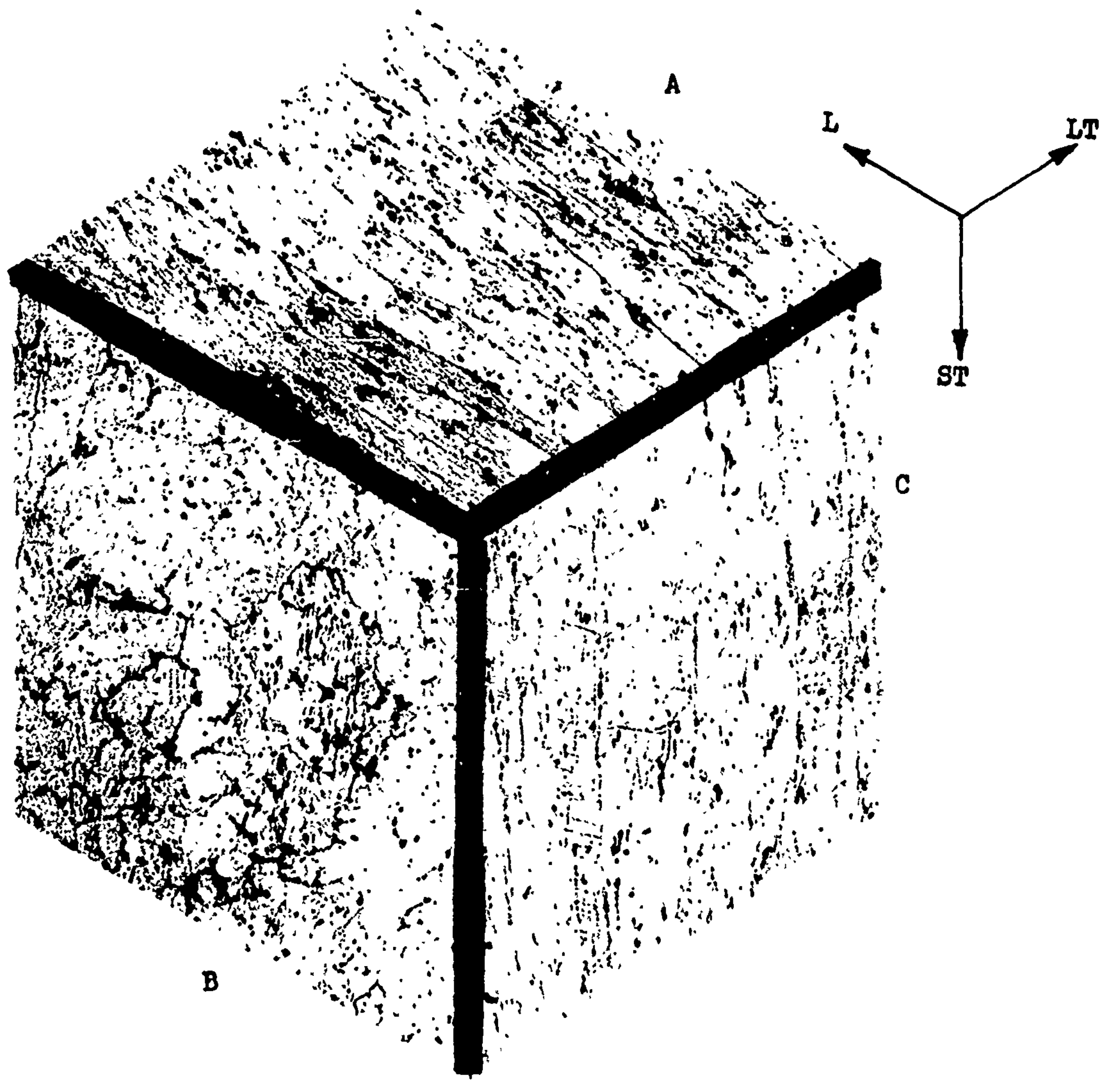


Figure 13b. Light Micrograph of Press Forged Block D10.

DISCUSSION

The feasibility of combining -T6 yield strength and -T73 stress-corrosion resistance in a single thermal-mechanically treated form of 7075, using conventional equipment, has been demonstrated conclusively in this program.

Yield strengths in the 70,000 to 75,000 psi range, together with stress-corrosion lifetimes at least as long as or longer than those of 7075-T73 specimens, were achieved by a simple two-step process. This process consisted of (1) an overaging treatment wherein 7075-T6 was heated for 5 or 10 hours at 350 F; and (2) a press forging operation wherein the overaged material was given a 20% reduction in the longitudinal direction of grain orientation (tensile and stress-corrosion properties were measured in the short transverse direction). The elimination of high stress concentrations, particularly those due to sharp edges and corners, in the pressed material, made it possible to perform the press forging at ambient temperature. The risk of overaging and of a concomitant loss in strength was thus reduced. A postheat treatment following the forging was found to be unnecessary.

The desired properties were obtained in the center (or as close to the center as it was possible to measure) of rolled stock originally ~3 1/8 inches in thickness, and in the center of forged stock measuring ~4 inches originally. The results of hardness traverses indicated that

the hardness gradients which were present in the blocks following heat treatment were nearly always eliminated by press forging. A 20% press forging reduction was thus highly effective in imparting uniform properties to 3 to 4 inch-thick blocks.

A very important principle has been demonstrated in this study, viz. that the directionality of grain structure and associated structures (such as undissolved particles) in 7075 aluminum can strongly affect the outcome of a mechanical working operation, depending on the direction in which the working forces are applied. It was shown that if the starting material was press forged in the short transverse direction, the degree of strengthening was considerably higher in the longitudinal direction than in the short transverse direction, and the converse was shown also. The large strength increments that were obtained in plate were accompanied by little or no loss in ductility. There is no obvious explanation for this interesting finding.

The present method of maximizing the work hardening in a particular direction by the application of forces in another (perpendicular) direction may be applicable to all structurally anisotropic alloys. With the proper selection of starting material (e.g., rolled plate instead of hand forging) it appears possible to achieve strengthening at no sacrifice in ductility.

CONCLUSIONS

1. It is possible to obtain the yield strength (≥70,000 psi) of 7075-T6 together with the stress-corrosion resistance of the -T73 temper in a single thermal-mechanically treated form of 7075 alloy.
2. The thermal-mechanical treatment that proved most successful in raising the short transverse properties consisted of an overaging treatment followed by a press forging reduction in the longitudinal direction of grain orientation. When this treatment was performed on plate stock, the strengthening was accompanied by little or no loss in ductility.
3. The results of an exploratory heat treatment incorporating several departures from standard practice were encouraging, but much work remains to be done before the optimum parameters can be established.

FUTURE WORK

The results reported herein open a whole new area for study. A fundamental program should be undertaken, which seeks essentially to correlate certain orientation-dependent structural and property characteristics. This program should include an extensive (light, scanning and thin film electron) microscopy study of plate and forged stock that has been press forged in one of the three main directions of grain flow. The starting blocks should include thicknesses as large as 8 inches. The program should include also a texture study using X-ray diffraction techniques.

A program conducted along the suggested lines should contribute further to the elucidation of the stress-corrosion mechanism in 7075 and other high strength aluminum alloys. The work hardening mechanism, particularly its dependence on grain orientation and its effect on stress-corrosion properties, should also become clearer for this group of alloys. The results of the fundamental program should reap numerous practical benefits. Potential applications include all structures and parts based on structurally anisotropic alloys (ferrous and non-ferrous) where high strength/ductility combinations are required. These applications may or may not involve stress-corrosion cracking.

REFERENCES

1. Jacobs, A. J., "Study of Stress-Corrosion Cracking of Aluminum Alloys," Final Report for Period 6 April 1966 to 5 April 1967, Naval Air Systems Command, Contract NOw 66-0309d, Rocketdyne, A Division of North American Aviation, Inc., Canoga Park, California, Report No. R-7026 (May 1967).
2. Jacobs, A. J., "The Role of Dislocations in the Stress-Corrosion Cracking of Aluminum Alloys," Final Report for Period 6 May 1967 to 5 May 1968, Naval Air Systems Command Contract N00019-67-C-0466, Rocketdyne, A Division of North American Rockwell Corporation, Canoga Park, California, Report No. R-7476 (June 1968).
3. Jacobs, A. J., "Optimizing the Combination of Strength and Stress-Corrosion Resistance of 7075 Aluminum by Thermal-Mechanical Treatments," Final Report for Period 15 September 1968 through 15 March 1969, Naval Air Systems Command Contract N00019-68-C-0433, Rocketdyne, A Division of North American Rockwell Corporation, Canoga Park, California, Report No. R-7822 (April 1969).
4. Embury, J. D. and R. B. Nicholson, J. Aust. Inst. Met. 8, 76 (1963).
5. Lorimer, G. W. and R. B. Nicholson, Acta Met. 14, 1009 (1966).
6. Jacobs, A. J., "The Effects of Point Defects and Dislocations on the Stress-Corrosion Susceptibility of Aluminum Alloys, Interim Report, NASA Contract No. NAS8-20471, Rocketdyne, A Division of

North American Rockwell Corporation, Canoga Park, California, Report No. R-7364, 25 February 1968.

7. Sprowls, D. O. and R. H. Brown, "Resistance of Wrought High-Strength Aluminum Alloys to Stress Corrosion," Technical Paper No. 17, Aluminum Company of America, Pittsburgh, Pennsylvania (1962).